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H and K Band Methane Features in an L Dwarf, 2MASS 0920+35[1]

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ABSTRACT

We have obtained near-infrared spectra of three L dwarfs discovered by 2MASS, 1506+13 (L3), 1507-16 (L5), and 0920+35 (L6.5). From the comparison of the H and K band spectra of these L dwarfs, we have found the presence of methane absorption in 0920+35. This implies that detectable methane absorption in the H and K bands, usually considered the signature of a T dwarf, can be present in objects classified optically as late L. Methane detection in L dwarfs is consistent with the presence of a dust layer deep in the atmosphere as the unified model of Tsuji suggests.

Subject headings: stars: low-mass, brown dwarfs — stars: late-type

1. Introduction

Companion searches around nearby stars discovered first two ultracool dwarfs which belong to spectral types later than M. In 1988, a brown dwarf candidate, GD 165B, was found as a companion to a white dwarf (Becklin and Zuckerman 1988), and finally in 1995, the first cool brown dwarf, Gl 229B, was found as a companion to a young M dwarf (Nakajima et al. 1995). Starting from 1997, the number of ultracool dwarfs was significantly increased by the discoveries by sky surveys, DENIS (Delfosse et al. 1997), 2MASS (Kirkpatrick et al. 1999, Burgasser et al.

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1999), and SDSS (Strauss et al. 1999) and now ultracool dwarfs form two distinct spectral types 'L' and 'T' (Kirkpatrick et al. 1999). L dwarfs which are cooler than M dwarfs are selected by red color in the visible or near infrared ($J - K > 1.3$) and their subclasses are defined by optical red spectra. T dwarfs which are even cooler than L dwarfs are selected by very red color in the visible or very red visible to infrared color and defined by the presence of methane in the near-infrared spectra. T dwarfs are blue in the near infrared ($J - K \approx 0$). As of writing of this letter, more than one-hundred L dwarfs and more than twenty T dwarfs are known in the literature, including L/T transition objects (Kirkpatrick et al. 2000, Burgasser et al. 2001, Leggett et al. 2000). The L/T transition objects or early T dwarfs show both methane and carbon monoxide in their K band spectra and have $J - K$ colors intermediate between L and T dwarfs.

From the point of view of observations, the sequence from L to early T to T dwarfs appears natural and there are a certain number of sample objects in each subclass of L dwarfs, early T dwarfs, and later T dwarfs. However, there are issues related to the L/T transition that need to be resolved before we fully understand these ultracool dwarfs.

First of all, we need a theoretical explanation of the L/T transition process in which the behavior of colors and spectra must be understood. In this paper, we compare the observed L dwarf spectra with the unified models by Tsuji (2001). The models explain the behavior of the infrared colors through the sequence and approximately reproduce the spectra of L and T dwarfs.

Another issue is the presence of methane in L dwarfs. In the discovery paper of the first DENIS L dwarfs, Delfosse et al. (2000) reported an apparent detection of methane in DENIS 0205-11AB (L7V) in the K band. However, Tokunaga and Kobayashi (1999) obtained a spectrum of this object and concluded that the 2 μm feature was due to H_2 collision induced absorption (H_2 CIA). Since then no researchers have claimed the presence of methane in late L dwarfs in the K band (Kirkpatrick et al. 1999,Reid et al. 2001). On the other hand, the presence of methane in L dwarfs was confirmed by L band spectroscopy of a L5V and L8V by Noll et al. (2000). So methane exists in L dwarfs and it is worth revisiting the features in late L dwarfs in the H and K bands taking into account the possible presence of methane absorption.

2. Observations

Observations were carried out at the Subaru telescope on 2001 March 3 and 4 UT using the grism mode of the Infrared Camera and Spectrograph (IRCS) (Kobayashi et al. 2000). The slit width of $0\farcs6$ was sampled at $0\farcs058$ per pixel and the resolution was about 330 at J, H, and K. The targets were nodded along the slit and observations taken in ABBA sequence where A and B stand for the first and second positions on the slit.

2MASSW J1146345+223053 (henceforth 2M1146) was observed on March 3 UT. At each of the four nod positions, 120 s exposures were acquired and the ABBA sequence was repeated three times at J, With 120 s exposures, the sequence was repeated twice at H and one cycle of 300 s

exposures was obtained at K. Immediately after the observations of 2M1146, JHK spectra of SAO81983 (G5V) were obtained for the calibration of telluric transmission.

2MASSW J0920122+351742 (2M0920) was observed on March 4 UT. The ABBA sequence was repeated twice at J and H with 120 s exposures and one cycle of 300 s exposures was obtained at K. Immediately after the observations of 2M0920, JHK spectra of SAO61451 (G0V) were obtained for transmission calibration.

2MASSW J1507476-162738 (2M1507) was observed on March 4 UT. The ABBA sequence was obtained once at J and H with 120 s exposures, and at K with 150 s exposures. Before the observations of 2M1507, JHK spectra of SAO159054 (G2V) were obtained for transmission calibration.

Data reduction was carried out using IRAF. Argon lines were used for wavelength calibration. Telluric absorption was removed by dividing each object spectrum with the corresponding G star spectrum after stellar absorption features had been removed. The result was multiplied by a blackbody spectrum whose temperature is that of the effective temperature of the G star. For flux calibration 2MASS magnitudes were used to normalize the spectra. Boxcar smoothing of 11 pixel wide (slit width) was applied before obtaining the final spectra.

IRCS is designed so that optical throughput of the wavelength regions where atmospheric transmission is poor is low. Usable wavelength regions are 1.18-1.35 μm, 1.49-1.81 μm, and 1.95-2.4 μm respectively at J, H, and K. Final spectra are shown in Figure 1.

3. Detection of methane features

3.1. 2M0920

In Figures 2 and 3, H and K band spectra are normalized so that the portions of the spectra which are least affected by molecular absorption features overlap. To emphasize the locations of H_2O and CH_4 absorption features, the spectra of Gl 229B (Geballe et al. 1996) are also shown.

In Figure 2, flux depression of 2M0920 (solid line) is conspicuous compared to the other two objects and the absorption maxima at 1.63 and 1.67 μm due to CH_4 $2\nu_2 + \nu_3$ and $2\nu_3$ bands are seen. These absorption features are also found in Gl 229B and in the early T dwarf, SDSS 1254-0122 (Leggett et al. 2000). In Figure 3, flux depression of 2M0920 due to methane extending from 2.15 μm to longer wavelengths is obvious as is the 2.20 μm absorption maximum of the $\nu_2 + \nu_3$ band.

3.2. DENIS 0205-11AB

Since we have seen the methane features in an L6.5 dwarf, it is natural to revisit spectra of other L dwarfs. DENIS 0205-11AB (L7V) was the first L dwarf for which methane detection was suggested (Delfosse et al. 1997). DENIS 0205-11AB is the coolest of the first three L dwarfs discovered by DENIS. Tokunaga and Kobayashi (1999) obtained a K band spectrum of this object, confirmed the flux depression longward of 2.2 μm, but interpreted the feature as due to H_2 CIA. This object was also observed by Leggett et al. (2001) and Reid et al. (2001), but none of the authors mention the methane detection. Instead Reid et al. (2001) comment on the influence of H_2 CIA on late L dwarfs referring to Tokunaga and Kobayashi (1999).

Now we question the interpretation of the 2.2 μm feature based on H_2 CIA. Wavelength dependence of absorption produced by H_2 CIA was calculated by Borysow and Frommhold (1990). One of the characteristics of this absorption is that it is spectrally broad. The absorption feature is not apparent within a narrow spectral coverage unlike the 2.2 μm feature. If present, it should produce a large flux ratio between for example H and K bands, but should not cause an abrupt change within the K band. Here we conclude that the interpretation of the 2.2 μm feature as methane by Delfosse et al. (1997) was correct.

3.3. Other L dwarfs

Reid et al. (2001) present the JHK spectra of 2MASS 0310+16 (L8V) (Figure 8 of their paper). In the K band spectrum of this object, the 2.3 μm CO bandhead is very weak while the 2.2 μm feature is strong. The weakness of CO indicates that much of carbon is in CH_4. Reid et al. interpret the 2.2 μm feature as due to H_2 CIA, but we argue that the feature is naturally explained by methane.

Kirkpatrick et al. (1999) present the K band spectra of 2MASS 0850+10 (L6V) and 2MASS 1632+19 (L8V) (Figure 5 of their paper). The 2.2 μm feature is apparent especially in 2MASS 0850+10, but they deny the presence of methane. We again argue that the natural interpretation of this feature is methane absorption.

4. Discussion

4.1. Complication in classification

The detection of methane in the H and K bands of 2M0920 complicates the definition of the L/T transition. 2M0920 was classified as L6.5V by Kirkpatrick et al. (2000) based on red optical spectroscopy. On the other hand, Leggett et al. (2000) suggested that L/T transition objects which show methane in the H and K bands should be classified as early T dwarfs. The difficulty

may be arising from the fact that while L dwarfs are defined in the optical wavelengths, T dwarfs are defined in the near infrared.

4.2. Formation of methane bands in L dwarfs

Methane can be formed at low temperatures near 1000K under high densities, and detection of methane in Gl 229B was deemed as evidence for very low $T_{\rm eff}$ of this object (Oppenheimer et al. 1995). It was somewhat unexpected that methane was detected in L dwarfs by Noll et al. (2000), even if the methane bands detected was the strong ν_3 fundamental. It may appear to be more surprising that the weaker combination bands of methane at 1.6 and 2.2 μm are now detected in an L dwarf as shown in §3. Such new observations, however, may imply that our understanding of the photospheric structure of L dwarfs should radically be reconsidered.

It was generally thought that the photospheres of L dwarfs are dusty. However, simple dusty models of case B (Tsuji 2000), in which dust grains exist throughout the photosphere so long as the thermodynamical condition of condensation is fulfilled, cannot explain the formation of the methane bands at all as shown in Fig.4a. In fact, no trace of methane bands appears in any models of $T_{\rm eff}$ between 1500 and 1800K. The reason for this is that the strong extinction by dust masks the molecular bands on one hand and also the backwarming effect of dust grains makes the photosphere too warm for methane to form. On the other hand, dust segregated models (case C), in which dust once formed has precipitated below the photosphere and volatile molecules dominate the observable photosphere, easily show methane bands at 2.2 μm as shown in Fig.4b. In this case, weak methane absorption appears already at $T_{\rm eff}$ = 1800K and turns to be quite strong at the lower $T_{\rm eff}$'s (note that the solid and dotted lines in Fig.4 represent the cases with and without methane opacity, respectively). However, it is known that the infrared colors of such models are rather blue and incompatible with the observed red colors of L dwarfs. It is clear that none of these models of cases B and C offers an explanation for the presence of methane bands in L dwarfs.

A new model was developed based on the idea that warm dust should exist deep in the photosphere (Tsuji et al. 1999), and the observed infrared colors of L dwarfs can reasonably be reproduced by the unified models with a thin dust layer deep in the photosphere (Tsuji 2001). In these models, both dust formation and segregation processes are taken into account and the thin dust layer is generated naturally. The unified models are successful because the thin dust cloud is situated in the observable photosphere of L dwarfs and this fact explains why the infrared colors of L dwarfs are so red compared with those of T dwarfs in which the dust layer is situated too deep in the photosphere to give observable effects. At the same time, volatile molecules can reside in the upper photosphere above the dust cloud in L dwarfs and this opens a possibility for methane bands to be formed. We confirm that the methane bands near 2.2 μm appear and can be predicted to be reasonably strong for models of $T_{\rm eff}$ below about 1600K as shown in Fig.4c. Thus only the unified model with $T_{\rm eff}$ between 1500 and 1600K offers a reasonable account for the

presence of methane and, at the same time, for the red colors due to dust extinction.

5. Concluding Remark

Methane absorption features are present in the H and K band spectra of 2M0920 (L6.5). The K band methane feature is also seen in some other L dwarfs found in the literature. We have shown that objects that are optically classified as L can have methane absorption at $1-2.5$ μm. The presence of methane in L dwarfs is consistent with the prediction of the unified models of Tsuji (2001) in which the presence of a thin dust layer deep in the atmosphere is considered.

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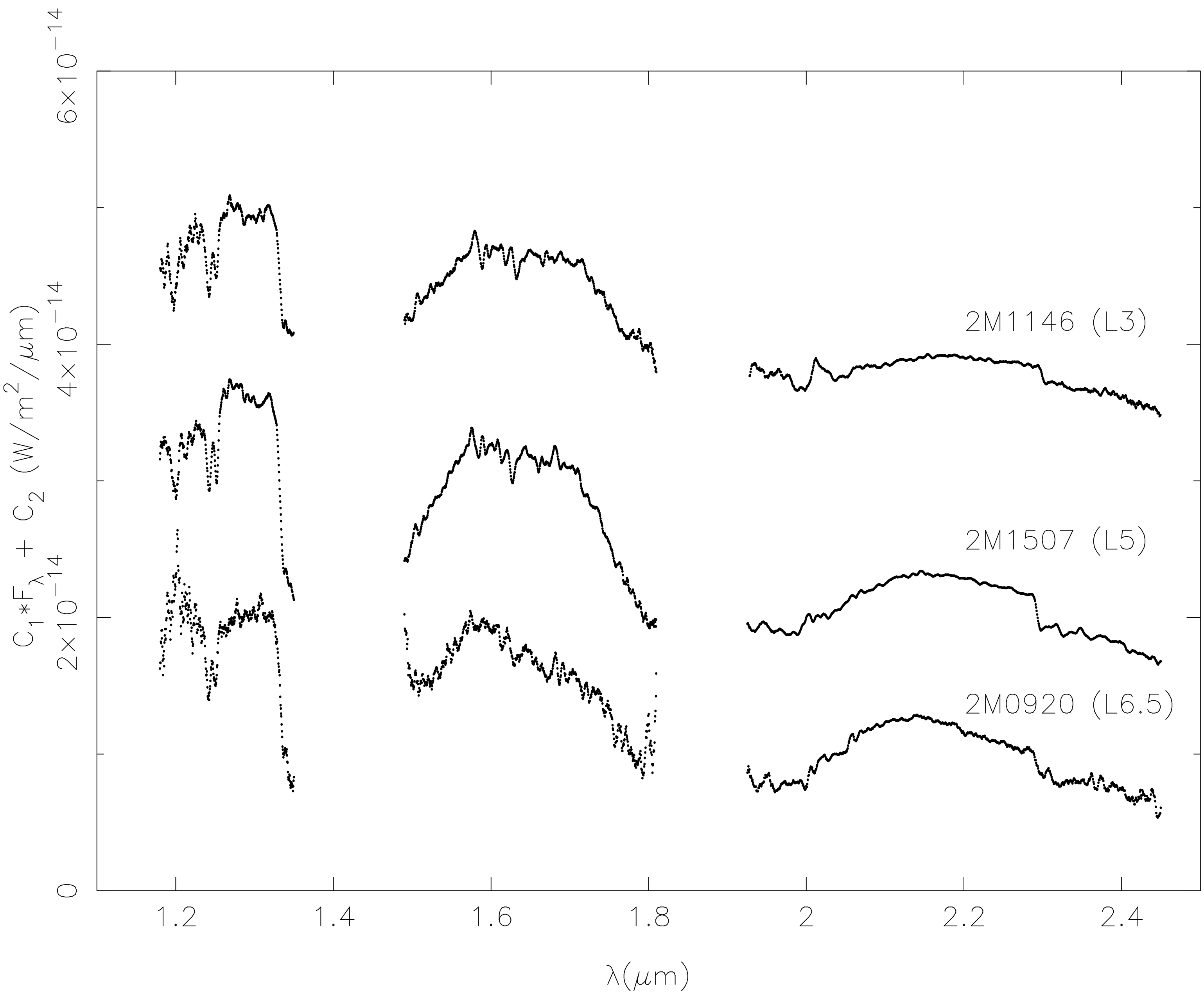
Fig. 1.— JHK spectra. They are linearly transformed by y = $C_1 * F_\lambda + C_2$ to make the comparison easy.

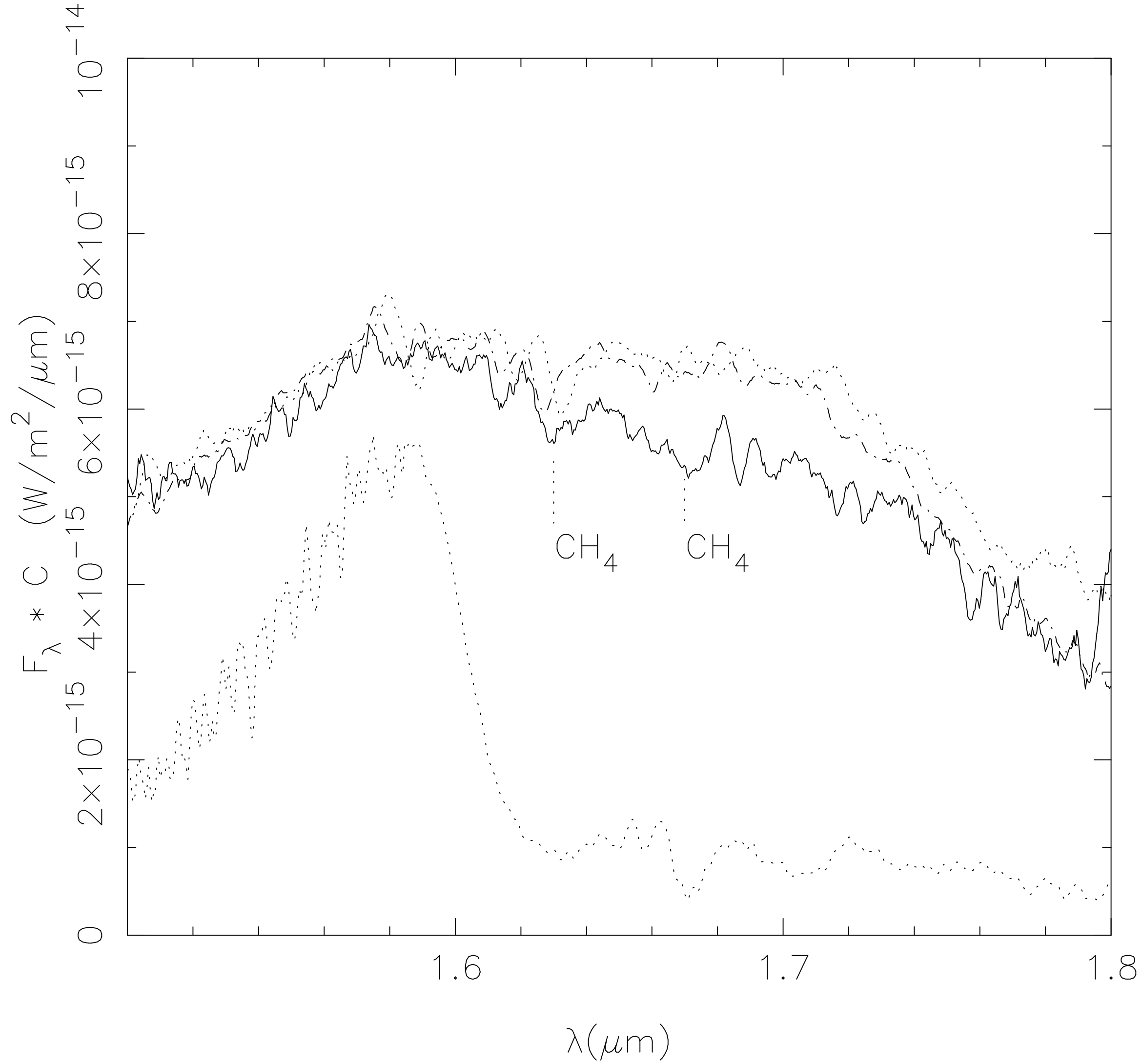
Fig. 2.— Comparison of H band spectra. Three spectra are normalized at 1.58 μm where molecular absorption has minimal effect. 2M0920 (solid line) shows flux depression compared to 2M1507 (dash-dot) and 2M1146 (dotted). The spectrum of Gl 229B (Geballe et al. 1996) is also shown for reference. The absorption maxima of CH_4 $2\nu_2 + \nu_3$ and $2\nu_3$ bands respectively at 1.63 and 1.67 μm are indicated.

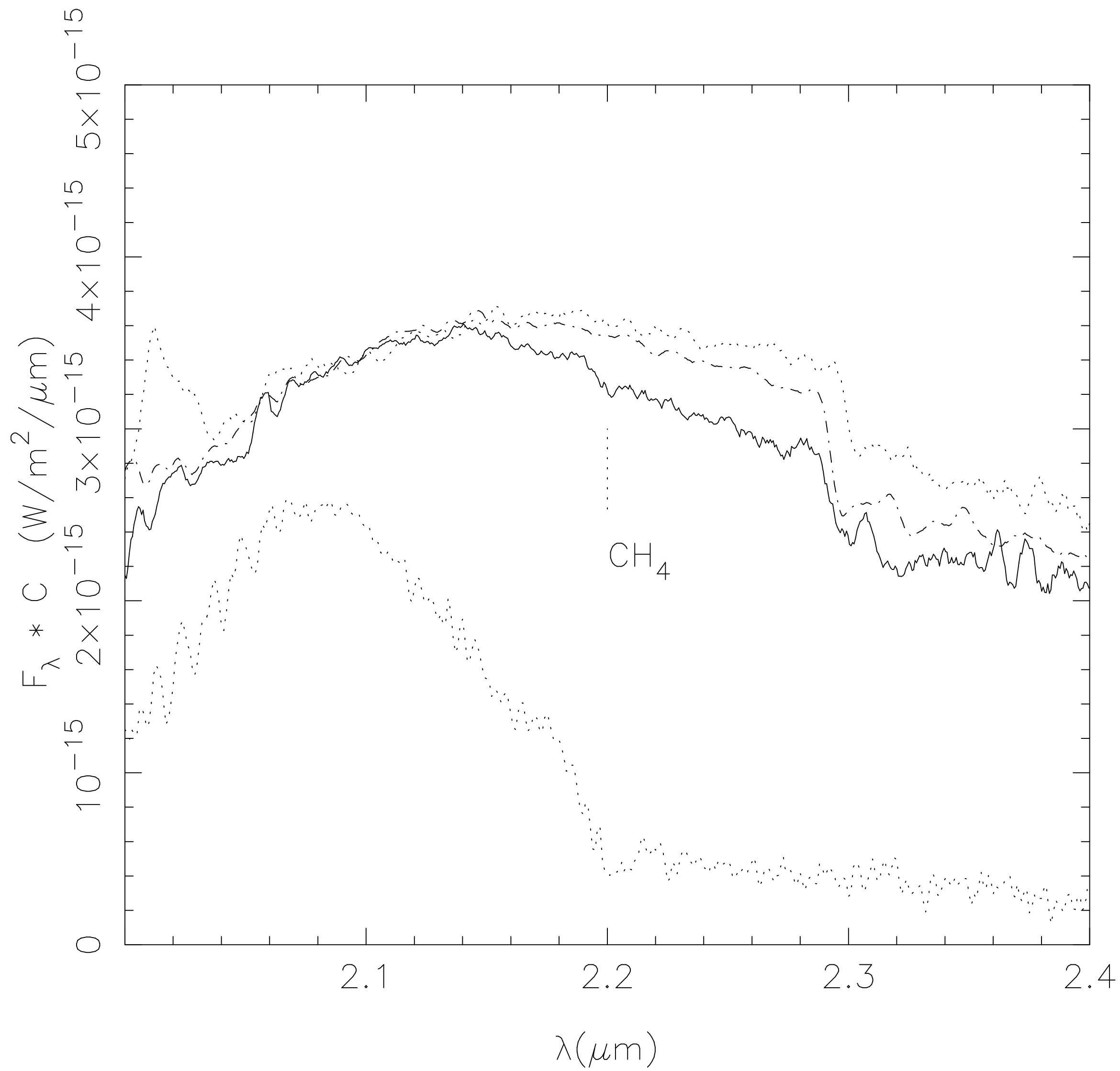
Fig. 3.— Comparison of K band spectra. Three spectra are normalized at 2.08 μm where molecular absorption has minimal effect. 2M0920 (solid line) shows flux depression compared to 2M1507 (dash-dot) and 2M1146 (dotted). The spectrum of Gl 229B (dotted, Geballe et al. 1996) is also shown for reference. The absorption maximum of CH_4 $\nu_2 + \nu_3$ band at 2.2 μm is indicated.

Fig. 4.— a) Synthetic spectra (F_λ in unit of 10^{-14} erg cm^{-2} sec^{-1} cm^{-1}) based on dusty models in which small dust grains form in LTE. The results with and without methane opacity show no difference, that is no methane band can be predicted by these dusty models for $T_{\rm eff}$ between 1500 and 1800K. b) The same as Fig.4a but based on the dust segregated models in which dust formed but precipitated below the photosphere. The solid and dotted lines represent the cases with and without the methane opacity. c) The same as Fig.4b but based on the unified models in which dust forms only in a thin cloud layer deep in the photosphere.

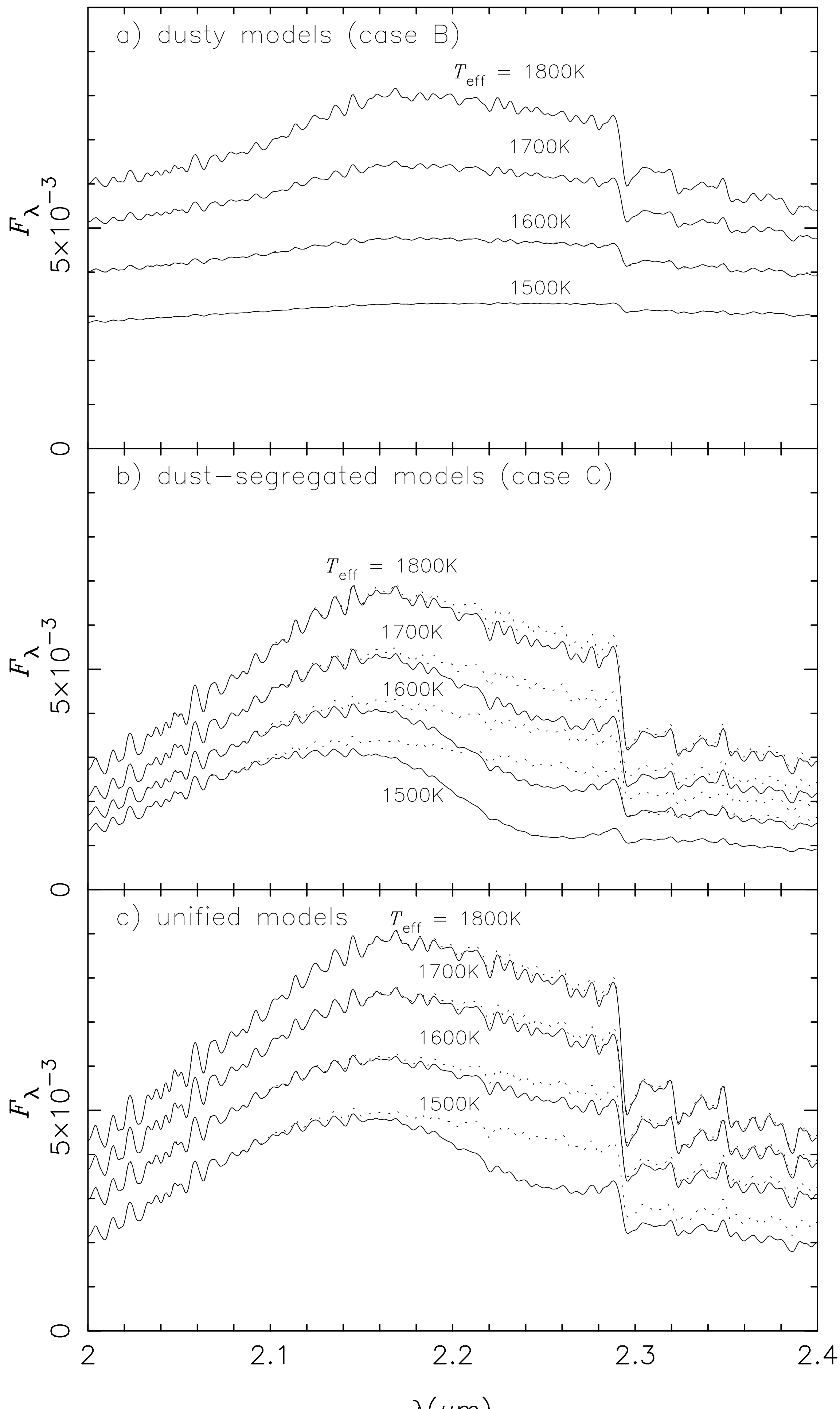


2M1146 (L3)
2M1507 (L5)
2M0920 (L6.5)
$C_1*F_\lambda + C_2$ (W/m^2/μm)
$\lambda(\mu m)$
0
2×10^{-14}
4×10^{-14}
6×10^{-14}
1.2
1.4
1.6
1.8
2
2.2
2.4


$F_\lambda * C$ (W/m^2/μm)
0
2×10^{-15}
4×10^{-15}
6×10^{-15}
8×10^{-15}
10^{-14}
CH_4
CH_4
1.6
1.7
1.8
$\lambda(\mu m)$



$F_\lambda * C$ $(W/m^2/\mu m)$
0
10^{-15}
2×10^{-15}
3×10^{-15}
4×10^{-15}
5×10^{-15}
2.1
2.2
2.3
2.4
$\lambda(\mu m)$
CH_4


a) dusty models (case B)
$T_{\rm eff}$ = 1800K
1700K
1600K
1500K
b) dust−segregated models (case C)
$T_{\rm eff}$ = 1800K
1700K
1600K
1500K
c) unified models
$T_{\rm eff}$ = 1800K
1700K
1600K
1500K
F_λ
5×10^{-3}
0
2
2.1
2.2
2.3
2.4
λ(μm)